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## Mark IVA Antenna Control System Data Handling Architecture Study

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*A high-level review was conducted to provide an analysis of the existing architecture used to handle data and implement control algorithms for NASA's Deep Space Network (DSN) antennas and to make system-level recommendations for improving this architecture so that the DSN antennas can support the ever-tightening requirements of the next decade and beyond. It was found that the existing system is seriously overloaded, with processor utilization approaching 100 percent. A number of factors contribute to this overloading, including dated hardware, inefficient software, and a message-passing strategy that depends on serial connections between machines. At the same time, the system has shortcomings and idiosyncrasies that require extensive human intervention. A custom operating system kernel and an obscure programming language exacerbate the problems and should be modernized. A new architecture is presented that addresses these and other issues. Key features of the new architecture include a simplified message passing hierarchy that utilizes a high-speed local area network, redesign of particular processing function algorithms, consolidation of functions, and implementation of the architecture in modern hardware and software using mainstream computer languages and operating systems. The system would also allow incremental hardware improvements as better and faster hardware for such systems becomes available, and costs could potentially be low enough that redundancy would be provided economically. Such a system could support DSN requirements for the foreseeable future, though thorough consideration must be given to hard computational requirements, porting existing software functionality to the new system, and issues of fault tolerance and recovery.*

### I. Introduction

The objective of this study was to provide an independent assessment of the capabilities of the current antenna control system data handling assemblies and to make rec-

ommendations for future subsystem development to be used as a guide during planned upgrades in the 1992 to 1995 time frame. The study focused on the data handling architecture of the antenna control system as it exists in the field and on its ability to handle the task of provid-

ing operator monitoring and control of the system. The system is built upon an elaborate message processing and transmission protocol that clearly shows the impact of ad-hoc system evolution in the form of late and lost messages. The study addresses the handling of the monitor and control data messages and the suitability of the design to sustain adequate message handling services.

The specific algorithms of the antenna control system have been reviewed, and a number were identified as having the potential to significantly impact the ability of the system to maintain timely responses. These algorithms include predict processing, correction for systematic errors, automatic boresighting correction, display generation, and collection of monitor data. Where alternate algorithms that require fewer system resources can be identified, these have been incorporated into the assessment and recommendations. Furthermore, although few criticisms have been levied against the lowest level servo-loop algorithms, it would be prudent to allocate increased system resources to them in order to support the evolution that should be possible in a healthy system with margin for growth.

The study was not constrained by implementation considerations associated with transition to a new system, system outages, and planned maintenance periods. These considerations are, however, real limitations on any upgrade plan, and, although they have not been addressed specifically, these issues have been reflected implicitly in the proposed data handling architecture in that the number of proposed changes to the system is minimized.

## II. Overview of the Current Architecture

Each antenna at a given site includes its own antenna control system. The Control Monitor Console (CMC) operator builds a link consisting of a Link Monitor Console (LMC), the Antenna Pointing Assembly (APA), and an antenna to enable communications with a spacecraft or for radio astronomy. Each APA is time-shared among up to three links. Because of the critical role of the APA in the link, a second APA is held in reserve as a backup, and can be automatically switched into action in case of failure. The control system architecture is defined as the sum of the subsystem functions, their assignment to hardware elements, and the resulting topology (Fig. 1). The antenna physical interfaces are not shown, but they consist of angle encoders, gimbal motor rate commands, and safety interconnect logic connected to the Antenna Servo Controller (ASC), Antenna Control and Monitor (ACM), Master Equatorial Controller (MEC), and Subreflector Controller (SRC).

The principal functions of the antenna control system consist of antenna pointing control, antenna performance monitoring, and maintenance support and fault isolation.<sup>1</sup> Partitioning these functions into subunits begins with the APA, which receives and processes directives addressed to the control system. The major APA functions include<sup>2</sup>

- (1) Processing predicts. The APA receives predicts from the LMC specifying antenna attitude and corresponding time at coarsely spaced intervals. The predicts are interpolated in time and coordinate transformed.
- (2) Performing automatic boresight correction (Conical Scan [CONSCAN]). Receiver automatic gain control (AGC) data are collected over a 30-sec period and processed using a fast Fourier transform algorithm.
- (3) Monitoring status for performance and safety and providing operator displays.

The Antenna Control Subassembly (ACS), one of which is dedicated to each antenna, is assigned to an APA by the CMC for a given link. The ACS must be capable of operating successfully even during a switch from one APA to an alternative or a change in the controlling CMC. The major functions of the ACS include<sup>3</sup>

- (1) Pointing the antenna as directed by the APA. The predicts are refined, more coordinate transformations are applied, and systematic error corrections are added.
- (2) Participating in automatic boresight pointing by providing pointing angles to the APA and executing scan-drive pointing commands.
- (3) Monitoring and configuring antenna equipment.
- (4) Processing systematic error corrections. The ACS incorporates site-dependent systematic error corrections into the predicts. These corrections are used to offset biases introduced by gravity sag, atmospheric refraction, encoder bias, and axis misalignments. The systematic error correction tables are prepared off-line by the antenna engineer and stored with other configuration data in the LMC.

The ASC, MEC, and SRC control servo loops are similar to one another when viewed at the functional level.

<sup>1</sup> *DSN System Functional Requirements Document 820-20 Rev. A, General Requirements and Policies Through 1988*, JPL D-5081, vol. 1, change 3 (internal document), Jet Propulsion Laboratory, Pasadena, California, pp. 3-5, June 15, 1980.

<sup>2</sup> Op. cit., p. 3C-3.

<sup>3</sup> Op. cit., p. 3C-8.

On those antennas with an MEC, the ACS sends pointing commands to the MEC and the ASC is slaved to follow, with error signals originating from an autocollimator. The ACS provides corrected pointing predicts to the MEC and to the ASC as backup information, but corrects each predict using systematic error tables for the individual controller. In the event of a failure or loss of lock in the MEC, the ASC drops back to executing pointing commands from the ACS. At a high level, the servo-loop controllers perform the following functions:

- (1) Executing the antenna pointing commands via a servo control loop.
- (2) Monitoring and reporting the status of equipment.

### III. Analysis of the Current Architecture

Prior to any explanation of the problems that prompted the current study, it should be clearly understood that the system is currently fulfilling its intended role. Taken as a whole, the Mark IVA is a complex system that has served admirably for some 6 years. Improvements and fixes have been applied over this time in a layered fashion, and expectations have changed because of advances in technology and improved understanding of the practical requirements based upon experience. Nevertheless, there are anomalies on record, functions that are inoperable, and a pervasive sense among the operators that the control system gradually grinds to a halt during heavy loading after a few hours of use.

Well-defined symptoms of problems have been observed. Operators have experienced slow update rates for critical display information, lost messages, and floods of warnings that ultimately originate from a single event. This combination of problems has two effects. First, the congestion in the communications channels is aggravated, possibly causing interference with other functions. Second, the operator's ability to respond correctly and in a timely fashion to an event is impaired, because of the time delays associated with critical messages and the distraction caused by a flood of messages. Currently, each subsystem generates its own set of messages for the operator when problems are identified. Although problems are rated on an urgency scale from one to five, causality is difficult to trace. Thus, messages tend to proliferate through the system. One result of this is that the APA processor duty cycle has been observed at close to 100 percent.<sup>4</sup> Though an upgrade to a new, higher capacity processor for the

APA has already been approved, such an approach treats the symptom of the problem rather than the root cause, which lies in the system connectivity and functional allocations.

Many of the anomalies are related to new requirements or unmet expectations. For example, the antenna and sub-reflector positions are not logged, and the displays generated by the system are not as useful as they might be. The changes required to correct these anomalies can be adequately negotiated and implemented in the future, just as the many other changes to the system have been performed over the past years. Only a few of these reported anomalies reflect the system inadequacies that are the subject of this study. The system change process does draw attention, however, to a principal shortcoming of the system reflected in the lack of reserve Central Processing Unit (CPU) capacity to easily execute software repair and improvement. Furthermore, some algorithms and practices (e.g., CONSCAN) consume resources inefficiently, although they do not appear to have a major impact on the system performance. On the whole, the functional design of the system is adequate, given the original requirements and the use of the system as it has evolved.

Within the scope of this study there are several identifiable features of this architecture that impact the performance of the system. These features are candidates for change in a modified architecture:

- (1) The message passing system needs improvement. A significant portion of the observed behavior of the system is tied to message passing response, since any message or command originating at the LMC must pass through several subsystems prior to reaching its addressee. Most of these intermediaries perform some processing of the message, either translating or expanding its contents. This multi-level hierarchical message passing system results in significantly delayed information when any subsystem is highly loaded.
- (2) The control subsystems were implemented in computer hardware that, while current for the time, is significantly outdated by current standards. The hierarchical partitioning of the system may in fact be a derivative of the limitations of the then-current hardware. An alternative architecture built upon more capable hardware would place major functions entirely within one subsystem.
- (3) The communication channels slow the performance of the system, given the basis in message passing and the hierarchical topology of the system.

<sup>4</sup> R. D. Rasmussen and N. T. Brady, *Mark IVA Antenna Control System Data Handling Study Final Report* (internal document), Jet Propulsion Laboratory, Pasadena, California, February 9, 1990.

- (4) The existing hardware topology constrains the potential functional topology options. The physical serial communications lines severely restrict the possibility of reallocating functions or repartitioning message paths.
- (5) Logging and archiving of monitor statistics are not performed in a systematic manner. Typically, the operators disable the monitor data logging function because it slows down the system.

As a result of the existing multilevel architecture, detailed knowledge of the antenna subsystem is embedded in several subsystem elements. The operator is forced to know detailed, low-level start-up, operation, and fault isolation sequences. Hardware-specific errors are reported by every system. Operability and maintainability of the system would be substantially improved if each antenna subsystem received higher level commands and reported summary error conditions in a condensed, predigested format. Ideally, the operator might, for example, command initiation of a track for a specific spacecraft, and the antenna control subsystem would configure, point, and monitor automatically, based upon preconfigured tables and supervisory functions. While the antenna control proceeds automatically, a monitor function associated with the antenna would collect exceptions, filter and process messages, and provide critical advisories to the operator.

## IV. Specific Recommendations

### A. Predict Processing

Predict processing is a core function of the system and provides the directives for pointing the antenna control system. The system's communication and computation burdens would be significantly reduced if a single interpolation algorithm were used by the servo controller. Further reduction in computation could be achieved by using a single coordinate system for all predicts and delaying the conversion to the antenna-peculiar coordinate system until the predicts reach the servo controller.

Implementing these changes would reduce computations, memory and disk storage requirements, and communication channel message volumes. The algorithms appear to be well within the capability of current hardware. This amounts to the replacement of extensive tabular data with an on-demand generator function.

### B. Application of Systematic Error Corrections

The predicted pointing angles are corrected in the ACS for such systematic errors as gravity sag and atmospheric

refraction. Application of these corrections is not computationally intensive, since it involves combinations of table entries and simple interpolations. The only change recommended is to provide automatic selection of the proper tables without operator intervention, given the operational mode.

### C. Generation of Systematic Error Correction Functions

Determination of the proper systematic corrections is severely hampered with the current method of data monitoring. Logging should be reinstated, and the systematic error modeling and creation of the correction tables should continue to be done off-line. The antenna engineer should be supported with investigative access to the antenna, perhaps under the maintenance mode, to assist in identifying error mechanisms and parameters. The Program Office should continue to invest in the development of on-line error-tracking and system calibration capabilities. Future enhancements might include the incorporation of real-time calibration and error tracking.

### D. Generation of Operator Displays

Data for inclusion in displays are generated at all levels of the control system, and most of the displays themselves are generated in the APA. In general, displays should not be generated by any element of the antenna control system that must also execute a real-time control function such as CONSCAN, servo loops, or exception monitoring. The operator console or a new unit in the antenna control system should be used to build the displays directly from a new database without recurring inquiries acted upon by the servo-loop systems. This implies an attendant change from generation of data on demand to a policy of maintaining a database of status information. Monitor and display data should be passed in a compact, binary mode using agreed-upon data structures.

### E. Single Point Antenna Monitor and Control

The monitor and control functions contained in the current functional architecture of the antenna control system should be collected and utilized as a single point of representation for the antenna. The intent is to partition low-level knowledge of the configuration and error handling to functions within the antenna, leaving the LMC operator with a consolidated, high-level interface. This function, named herein the "antenna monitor and control function," is not significantly different from the original design role of the ACM subsystem. However, the ACM as presently implemented is too close to the mechanical interfaces of the

antenna hardware and, except for the watchdog activity, executes little monitoring and no control.

Several implementation issues support the reinstatement of an effective monitor and control function besides raising the level of the operator interface. An interface between the control room Local Area Network (LAN) and the antenna network is required to minimize undesired message traffic, buffer signals for the potentially long distance to the antenna, and allow for media differences between the two network domains. Thus, a computer system that hosts the monitor and control function that is located in the control room can serve as the internetwork gateway and electronic interface.

## V. Proposed Architecture

### A. Functional Architecture

To alleviate the observed performance problems of the current system, modifications to the architecture could incorporate one or more of the following (the top-level system diagram that incorporates these modifications is shown in Fig. 2):

- (1) A simplified message-passing hierarchy where the path from any sender to any receiver includes at most one, and preferably no, intermediate subsystems or logical tasks. The intention is to reduce message passing delays; when accompanied by consolidation of tasks within more powerful servo controllers, this can be readily accomplished.
- (2) Implementation of a network local to the antenna-control system that eliminates the point-to-point low-speed communication channels. This would establish each subsystem as a peer on the network and provide the physical mechanism to support direct addressing of all messages. Most reasonable network implementations will also provide reliable communications at substantially higher speeds than the present RS-232 protocol. Careful consideration must be given to the distance requirements, which, for some antennas, might reach 10 km from the control room to the antenna. Again, most reasonable network implementations can meet this requirement, although careful design is required, and slightly higher costs can be expected for the long-distance segments of the network.
- (3) Redesign of certain functions to reduce the computation, storage, and message volume associated with the algorithms. Specifically, predict processing might employ a single coordinate system and a single interpolation algorithm.
- (4) Consolidation of antenna monitor and control functions and implementation in a system that resides at the interface between the control room network and the antenna network.
- (5) Utilization of new, modern 32-bit commercial computer hardware with a real-time operating system kernel and network-based communications. This would provide significant flexibility in the design of the new architecture task structure and provide a basis for potential incorporation of fault tolerance through semiautomatic reconfiguration. The principal motivation for this change is to provide increased processing power and high-speed, standardized communications at relatively low cost.

The system functions would be retained and allocated to the logical units of the modified architecture. The principal differences are

- (1) CONSCAN, or automatic boresighting, is executed entirely within the servo controller.
- (2) Systematic errors are corrected at the servo controller.
- (3) The monitor and control function oversees operation of the antenna subsystem and maintains a database that is used to generate displays for the LMC.

### B. Principal Features of the Modified Architecture

The topology of the modified architecture represents a simpler hierarchy by replacing the APA and ACS with a single unit that is logically a part of the antenna control system and provides a network interface and high-level monitor and control functions. Elimination of the functions currently allocated to the APA and ACS is not proposed. All existing functions should be retained, although a few should be reformulated and hosted in new subsystems.

The antenna control subsystems are depicted as peers on a local network. This network might be implemented in several ways, for example, in Ethernet between separate computers or in shared memory among multiple processors on one common backplane. Such a network should support a virtual communications system defined in software, as might be done with Unix sockets or Transmission Control Protocol/Internet Protocol (TCP/IP) channels, and would provide reliable, high-speed communications at very low cost.

The architecture retains the MEC and SRC units, principally as logical functions. It might be entirely possible

to host these less intensive functions as tasks on the same CPU with the ASC. Hardware such as an MC68040 on the VMEbus or an i80486 on the Multibus II provide sufficient capacity to execute the current functions and servo loops. Economical systems with either Ethernet or back-plane networks are readily available.

An additional subsystem, the Antenna Monitor and Control (AMC), has been included in the architecture to provide a high-level interface to configure and control the antenna and to monitor the status of the antenna system. The AMC provides local access for maintenance, monitoring, or calibration, and provides data collection, analysis, and monitoring for identification of systematic errors, equipment failures, or anomalies in support of reconfiguration, and potentially even intelligent real-time oversight of operational status. These functions are probably quite similar to the original intent of the ACM, although the ACM as it has evolved is too intimately associated with the physical interfaces to the antenna to also host higher level functions and network connection needs.

The AMC takes on the display generation functions currently resident within the APA. Routine monitor data are collected and stored in the database within the AMC and utilized to generate displays as required by the operator. All high-level operator commands are expanded and sent directly to the subsystem that hosts the targeted task. For example, predicts and interpolation parameters are messaged directly to the pointing task resident on the ASC where the servo loop performs the interpolation and correction when required.

## VI. Implementation Options

Beyond the recommendation to rebuild the system in modern commercial software and hardware, several implementation and configuration options are available. The commercial market is well developed, with excellent product selection and price competition. A good development environment based upon Computer Aided Software Engineering (CASE) tools for real-time systems should be utilized and the control software rewritten based upon a real-time kernel. Where possible, the existing HAL-S and PL/M code should be converted to a current language that can be supported by the CASE tools and available programmers.

In the hardware arena, configuration options for the computers that host the antenna control system functions range from replicating the current configuration, which is

one CPU per chassis per subsystem, to one chassis with a few CPUs hosting all functions. Within this implementation framework, several development options exist that can contribute to improved reliability and the incorporation of fault tolerance. The necessity of such improvements depends entirely on the yet-to-be-developed detailed reliability requirements.

## VII. Summary and Recommendations

This study focused on the architecture of the antenna control system and its ability to handle the task of providing operator monitoring and control of the system as it has evolved and exists in the field. Recommendations for modifications to the existing architecture have been proposed and further investigation and design in key areas is required prior to final planning for the system upgrade. This section briefly summarizes these areas.

Detailed assembly-level requirements must be derived for such functions as error reporting, operator control of lower level devices, and status presentations. The system documentation consistently neglects the development of coherent propagation of requirements to the lower levels of the servo controllers.

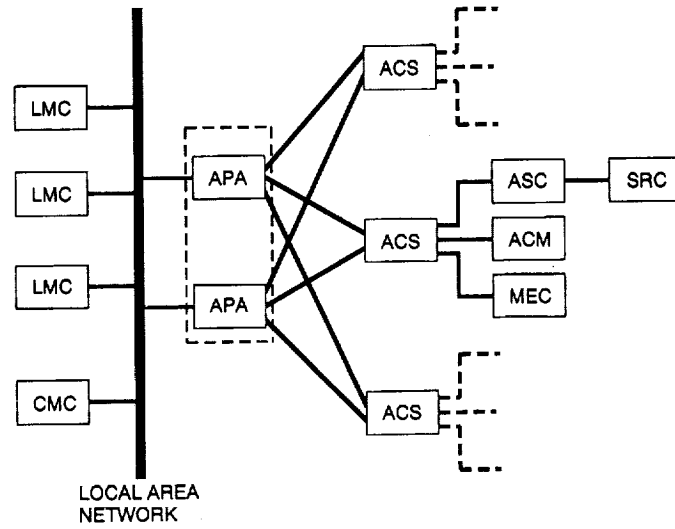
With derived requirements in hand, the modified architecture design can be continued. The immediate need is for a budgetary cost estimate for the upgrade. This can be obtained once CPU loads, communication channel capacities, and memory sizes are estimated from the functional descriptions and requirements. Since the system's overall costs are not very sensitive to the exact number of Single Board Computers (SBCs), attention should be directed to firming up the architecture configuration.

Considerable attention is required in the area of specifying the reliability requirements for the system to the level of detail that permits selection of a particular method. The current central requirement based upon a guaranteed not-to-exceed downtime is insufficient. Other derived requirements in the form of probability of failure, fail-safe or fail-tolerant design paradigm, or worst case failure are required to enable a design choice among such reliability enhancements as voting, hot spares, and fault-tolerant subsystems.

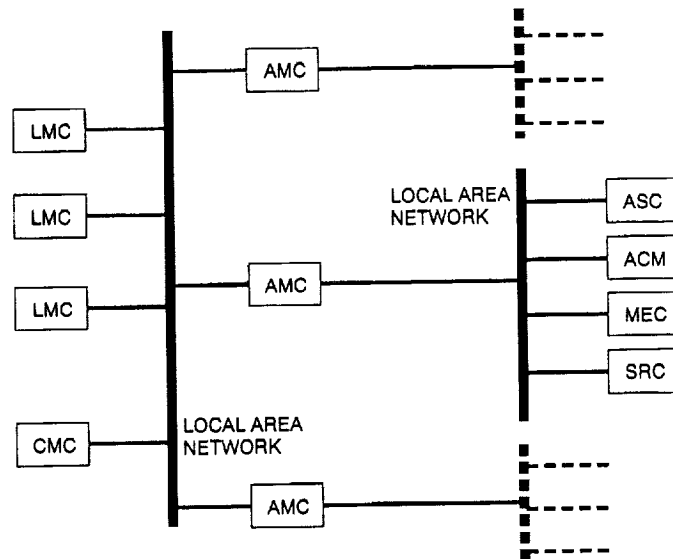
Development of an on-line error tracking and system calibration capability needs to be done first so that requirements can be integrated into the planned upgrade. Most probably, a development period of several years

will be required and installation in the antenna systems might occur after the upgrade period. With an early start on the development, capacity might be installed to accept later deliveries, or at least the system can incorporate the necessary "hooks" and access ports for eventual installation.

There are significant constraints associated with maintaining system services during the modification period that were excluded from the current study. Several means to achieve a phased, testable installation exist, and the ramifications and details would be worked out in the development plan.



**Fig. 1. Current system architecture.**



**Fig. 2. Modified system architecture.**